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INCIDENTAL PROBLEMS
IN
GAS-PRODUCER TESTS

BY

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CONTENTS.

	Page.
Introduction	5
Factors affecting proper length of tests	7
Practical importance of results	7
Limitations of present experiments	8
Determination of fuel-bed thickness	8
Effect of error in measurement	9
Beginning and closing with equal fuel-bed depth	9
Division of tests into periods	11
Fluctuations of fuel-consumption rate	11
Estimate of proper test duration	13
Summary and table	13
Temperature differences in fuel bed	15
Purpose and method of experiments	15
Temperature at different heights	17
Different horizontal positions	18
Causes of irregularities	20
Average results for each point	20
Process of gas formation	22
Differences with distance from axis	24
Requisite temperature for formation of CO	26
Summary	27

ILLUSTRATIONS.

	Page.
FIGURE 1. Cross section of gas-producer fuel bed	10
2. Variation in coal consumption per brake horsepower hour	12
3. Cross section of gas producer	16
4. Pyrometer tube	17
5. Gas-sampling tube	17
6. Curves of temperature variation with height above base of fuel bed	21
7. Variation of gas combustion temperature and British thermal units with height above base of fuel bed	23
8. Section of producer, showing temperature variation for height and distance from sides of producer	25



INTRODUCTION.

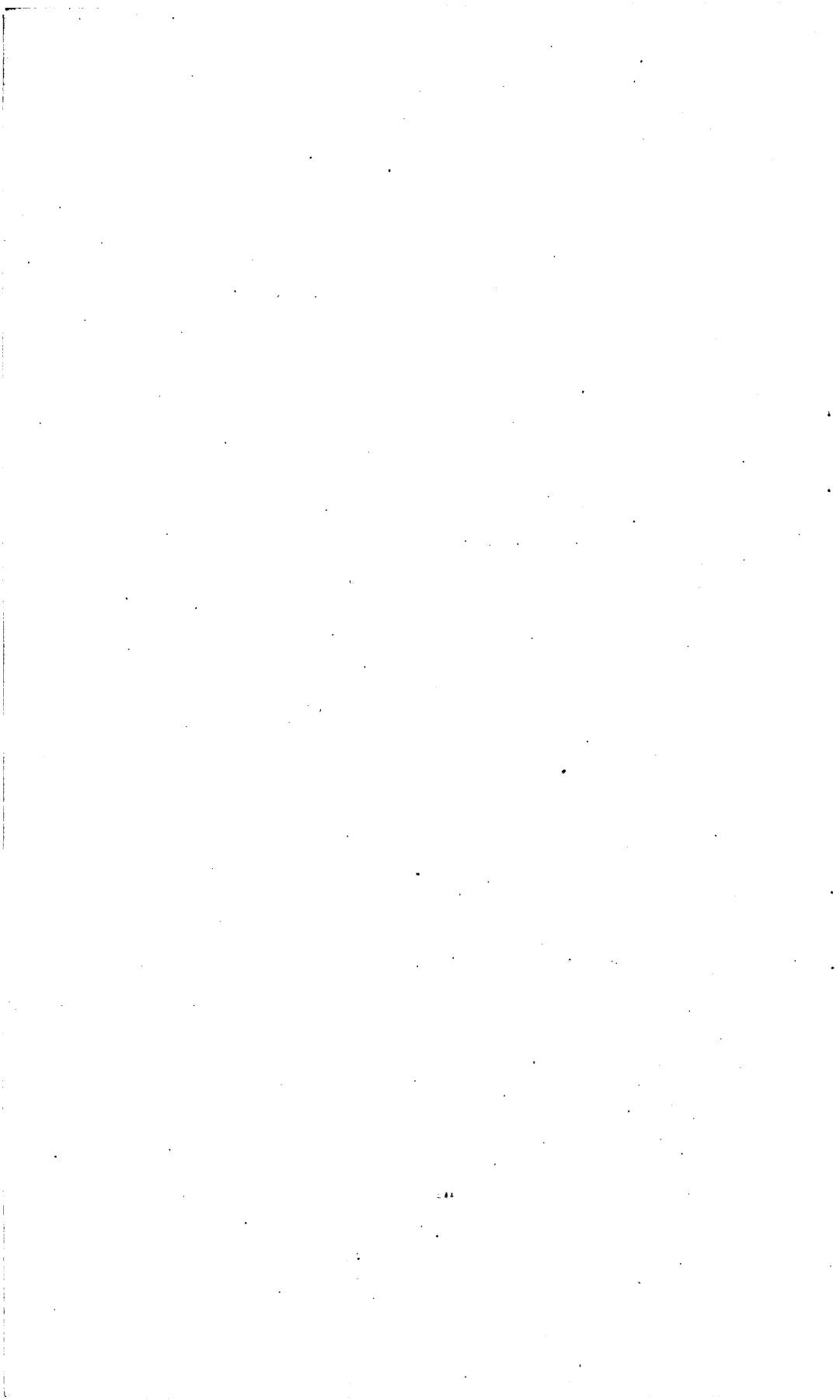
By J. A. HOLMES.

As part of its investigation of methods of increasing the efficiency of fuel resources, the United States Geological Survey is studying the general problems involved in the economic use of fuels in gas producers. In the course of this study many incidental problems of prime importance demand consideration. Among them is the determination, under practically constant conditions, of the duration of gas-producer tests necessary to reduce the possible error to a minimum. A discussion of this proper length of test period forms the first part of this bulletin.

An attempt to dispel some of the uncertainties that arise in an investigation or to account for some of the minor phenomena often necessitates a systematic and careful study of certain chemical, thermodynamic, or physical laws, or a combination of these, which in turn may result in information or conclusions of great value. Furthermore, seemingly unimportant observations often prove to bear directly upon the design, construction, or manipulation of the machine under test.

In attempts to improve the gas producer considerable attention has been given by manufacturers to such questions as fixing or isolating the combustible components of the tar, utilizing the waste heat of the producer for the generation of the steam required by the plant, applying the suction principle to bituminous coal and other tarry fuels, and many allied subjects. Little study, apparently, has been given to the physical-chemical conditions most suitable to the formation of hydrogen and of carbon monoxide, with a view to regulating the percentages of these gases in generators using fuels other than anthracite coal or charcoal.

An attempt was made to introduce such investigations when the operations of the government coal-testing plant began at the Louisiana Purchase Exposition in St. Louis in 1904, but owing to adverse conditions these problems were abandoned until the plant was transferred to Norfolk in 1907. The delay in beginning this line of investigations, together with the short testing season at Norfolk, limit the second part of this report to preliminary physical-chemical studies, which, however, are sufficiently significant to warrant careful examination pending more complete researches, which are to be carried on at the station recently located in Pittsburg.



INCIDENTAL PROBLEMS IN GAS-PRODUCER TESTS.

FACTORS AFFECTING PROPER LENGTH OF TESTS.

By R. H. FERNALD and C. D. SMITH.

PRACTICAL IMPORTANCE OF RESULTS.

The recent development of producer-gas as an important element in power installations has led to a large number of tests of such plants within the past few years. Such tests have been conducted from several standpoints: (*a*) By the United States Geological Survey as a means of determining the economic value of different fuels when used in gas producers, and also the relative value of the fuels in the producer and under the steam boiler; (*b*) by the purchaser of such installations for a satisfactory verification of points in the contract; (*c*) by the gas-producer manufacturers to assist in determining questions of proper design, bases for guaranties in contracts, etc.; and (*d*), unfortunately, by some promoters to obtain results purely for advertising purposes, at the same time conveying the impression that the absurd figures quoted have been obtained by carefully conducted tests by disinterested parties.

Some of the test results reported by certain gas-producer manufacturers are so absurd that no careful purchaser will be deceived; but, unfortunately, the alluring guaranties and special inducements regarding the cost of the installation have caught enough unwary buyers to injure seriously the business of reputable concerns. It is not uncommon to pick up advertising material that states a fuel consumption per horsepower per hour based on tests of two or three hours' duration only, in which the total coal charged during that period was from 20 to 30 pounds. The producers in such tests are of course of small sizes, but the principle is the same for all. The initial fuel bed built up before the test is started amounts to several times the quantity of fuel charged during short-interval tests, and the amount of gas that may be drawn from this foundation bed is an unknown quantity. It may be very small or may reach a large percentage of

the total gas used during short tests, depending on the carelessness or cleverness of the superintendent of the test.

Of course the claim is made that at the end of the test the fuel bed is always brought to the same condition that it was in at the beginning, but experience in this direction need not be great to show that such conditions are practically impossible in tests of short duration. The error introduced by such an assumption may be sufficiently great to make the recorded results absurd. In fact, the percentage of possible error may be so large that it is only necessary to predetermine the desired fuel consumption per horsepower per hour and trust to the clever manipulation of the operator to secure that result.

It is no wonder, then, that tests showing a consumption of only 0.6 pound of coal per horsepower per hour are often reported; and apparently it is only necessary for some daring promoter to decide that a horsepower should be developed with a consumption of 0.25 pound per hour for tests to be reported that show this figure.

LIMITATIONS OF PRESENT EXPERIMENTS.

For accurate tests of gas producers and for a true determination of the fuel consumption, either (a) the conditions of the fuel bed at the beginning and at the end of the test must be positively known, or (b) the test must be of sufficient duration to practically eliminate the uncertainties that arise from varying conditions of the bed. Inasmuch as the first method is usually out of the question, it is necessary to resort to the second, at the same time securing as uniform conditions as possible in the fuel bed.

The exact relation between the size of producer and the proper length of test for measuring with a reasonable degree of accuracy the amount of coal consumed has not yet been fully determined at the fuel-testing plant of the Geological Survey, but some light may be thrown upon this important point by some of the results secured in the course of these tests.

During the tests at St. Louis very little information relating to the subject of this report could be obtained, because the average length of test was restricted to fifty hours or less by the limited supply of each variety of fuel furnished for the trial. At Norfolk, however, the conditions were more favorable in this respect, and four tests were of sufficient length to permit some study of the problem.

DETERMINATION OF FUEL-BED THICKNESS.

The producer used was of the pressure type. It was rated at 250 horsepower and was 7 feet in internal diameter. The initial fuel bed, built up before the official start of each test, amounted to about 5,000 pounds of coal.

The method of measuring the thickness of the fuel bed was as follows: Around the sides of the producer and located 90° apart were four sets of sight holes, designated A, B, C, and D. Each of these sets consisted of four holes placed vertically 6 inches apart, thus giving a vertical range of 18 inches for observation. During the operation of the plant the top of the ash bed was maintained within this range. The distance from the producer top to the top of the ash bed was taken as the average of the four measurements at the points A, B, C, and D. In a similar manner the distance from the producer top to the top of the fuel bed was taken as the average of measurements at four corresponding points. The difference between these two measurements gave the thickness of the bed, and, with the weight of a given volume of the fuel known, the total weight of the fuel bed, on the basis of the assumptions noted, could be determined.

EFFECT OF ERROR IN MEASUREMENT.

The thickness of the fuel bed as determined by assumption, or even by measurement, in the producer used for these tests, may easily be in error from 4 to 6 inches. The error at the beginning may or may not be neutralized by an equal error at the close of the test period. The magnitude of the error depends on the state of the fuel at the time the measurements are taken. With a bed 7 feet in diameter it will amount to from 500 to 800 pounds if the fuel happens to be green coal ("coal as fired"); but as the uncertainty in measuring is at the bottom of the fuel bed, just above the ash line, where the fuel is not green coal but coke, an error in weight of fuel estimated from measurements of the depth of bed probably equals the weight of the corresponding volume of coke instead of green coal. For the fuel used during these tests, the ratio of the weights of equal volumes of coke and coal is approximately 1 to 2. Hence, there may be an error, either positive or negative, due to the fuel-bed measurements alone, of 400 pounds of coke.

It is readily seen that even if the essential conditions of the bed at the end of a test duplicate those at the beginning there is still considerable difficulty in determining the exact fuel consumption, owing to inaccuracy in the measurements indicated. It is evident, however, that a test may be continued to such length that this error of 800 pounds of coal, or 400 pounds of coke, will be a small percentage of the total fuel consumed.

BEGINNING AND CLOSING WITH EQUAL FUEL-BED DEPTH.

Although a test may continue so long that the error due to inaccurate measurement is eliminated, a second serious difficulty is encountered if the depth of bed at the end of the test does not equal

that at the beginning. For example, suppose the condition of the fuel bed to be practically the same at the beginning and end of the test, except in thickness. Let A, figure 1, represent the thickness of such a bed at the beginning and B its thickness at the close of the test; then the fuel consumed is the amount actually fired, plus some quantity represented by C. Again, the fuel bed at the beginning may be thicker by an amount C than at the close. It is evident that in either case a correction must be made in the weight of fuel used equal to the weight of the volume C. But this volume may consist entirely of fresh coal, entirely of coke, or of a mixture of the two in any proportion.

In the producer used for these tests a layer of green coal 1 inch thick was equivalent to about 150 pounds; then if C is 10 inches and

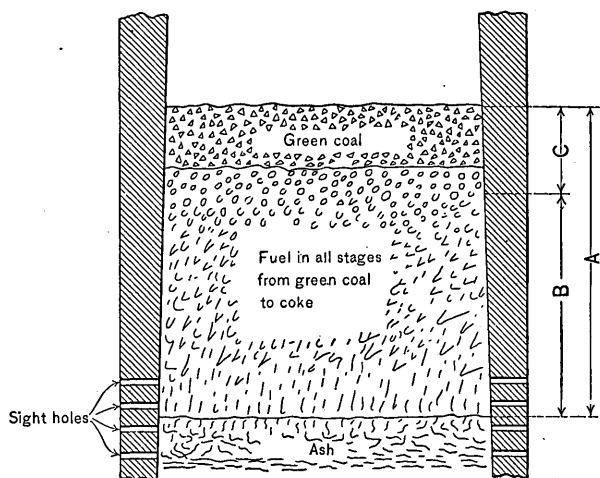


FIGURE 1.—Cross section of gas-producer fuel bed.

the fuel in this volume is green coal the correction to be made amounts to 1,500 pounds. If, however, the fuel occupying the volume C is assumed to be green coal, but is actually coke, an error of 750 pounds is introduced. On the other hand, if the volume C is assumed to be filled

with coke and it is actually filled with green coal, there is still an error of 750 pounds, but in the opposite direction. The error may, therefore, vary between these two limits according to the assumption made and the character of the fuel actually in this volume C.

Owing to the lack of positive information on the subject, it was formerly the custom at the fuel-testing plant to allow for volumetric differences in the fuel bed, due to changes in the level, by adding or subtracting the weight of an equivalent volume of the green coal ("coal as fired") used in the test; but during the Norfolk work special attention was given to closing each test with a fuel bed of the same thickness as at the start, so that the figures given for this series of tests for the average coal consumption per horsepower per hour for the entire test may be regarded as essentially correct.

DIVISION OF TESTS INTO PERIODS.

In order to study conditions more carefully, each test was divided into several periods and the fuel consumed in the producer was calculated for each period. The desirability of having the fuel-bed level the same at the beginning and at the end of each of these short periods was not appreciated until the calculations had been made. This variation in depth (C, fig. 1) for some of the periods was as much as 10 inches, which, with a 7-foot producer, means a considerable volume.

If the periods into which these tests are divided are only eight hours, the fuel consumption for each period amounts to only 1,800 pounds, approximately. If it so happens that an error of 750 pounds due to changes in the fuel-bed thickness is combined with a 400-pound error due to inaccurate measurement of the depth of bed, a total error amounting to 1,150 pounds may result. The percentage of possible error in calculating fuel consumption for short periods is obviously great. With a period of twenty-four hours and a fuel consumption of about 5,400 pounds the percentage of possible error is much less, but is still over 20 per cent.

Of the tests used in studying this subject, No. 164 was divided into periods of eight hours each, while tests 165, 166, and 168 were divided into periods of twenty-four hours. The table on page 14 gives the amount of coal actually charged into the producer during each period, and also the amount of coal consumed for each period as corrected (on the green-coal basis) for changes in the volume of the fuel bed, according to the methods indicated above.

FLUCTUATIONS OF FUEL-CONSUMPTION RATE.

It will be noted that the load carried, or brake horsepower, is very uniform except in one or two instances, and for this reason a fairly uniform fuel consumption would naturally be expected. It will be seen from Table 1, however, that in the first three tests, Nos. 164, 165, and 166, the apparent fuel consumption per period and also per brake horsepower per hour for each period is far from uniform. The last column in the table gives the fuel consumption per brake horsepower per hour for the time from the start of the test to the end of each period. These values approach an average, and in general become more uniform as the test proceeds. It was expected that they would become so uniform as to practically determine the necessary duration of tests in plants of the given type and size, but of the four tests made only one, No. 168, was entirely satisfactory in this respect. In No. 165, for example, the average fuel consumption per brake horsepower per hour at the end of the ninth period, or 216 hours, was 0.84 pound, and at the end of the tenth period, or 240 hours, it was 0.90 pound, an

The figure consists of four vertically stacked line graphs, each representing a different test (164, 165, 166, and 168). The common y-axis for all graphs is 'Pounds consumed in producer per boiler horsepower hour', ranging from 0.40 to 1.40. The common x-axis is 'Hours', ranging from 0 to 250. Each graph contains three data series: a dashed line with open circles for 'For period', a solid line with open circles for 'From beginning of test to end of period', and a solid horizontal line for 'Average for entire test'.

TEST 164

Hours	For period	From beginning of test to end of period	Average for entire test
25	1.25	0.85	0.95
50	1.40	0.90	0.95
75	1.18	0.92	0.95
100	1.12	0.95	0.95
125	0.95	0.95	0.95
150	1.10	0.95	0.95
175	0.75	0.95	0.95
200	0.95	0.95	0.95
225	0.95	0.95	0.95
250	0.95	0.95	0.95

TEST 165

Hours	For period	From beginning of test to end of period	Average for entire test
25	0.72	0.72	0.88
50	0.98	0.85	0.88
75	0.95	0.90	0.88
100	0.92	0.90	0.88
125	0.95	0.92	0.88
150	0.78	0.88	0.88
175	0.95	0.92	0.88
200	0.88	0.88	0.88
225	0.82	0.85	0.88
250	1.35	0.90	0.88

TEST 166

Hours	For period	From beginning of test to end of period	Average for entire test
25	0.90	0.90	0.88
50	0.70	0.80	0.88
75	0.80	0.80	0.88
100	1.10	0.88	0.88
125	0.75	0.85	0.88
150	0.85	0.85	0.88
175	1.08	0.88	0.88
200	0.95	0.90	0.88
225	0.85	0.88	0.88
250	0.88	0.88	0.88

TEST 168

Hours	For period	From beginning of test to end of period	Average for entire test
25	0.92	0.90	0.90
50	0.95	0.90	0.90
75	0.98	0.90	0.90
100	0.80	0.90	0.90
125	0.92	0.90	0.90
150	0.95	0.90	0.90
175	0.95	0.90	0.90
200	0.88	0.88	0.90
225	0.90	0.88	0.90
250	0.98	0.90	0.90

FIGURE 2.—Variation in coal consumption per brake horsepower hour.

fuel consumption per brake horsepower per hour for the entire test; the points connected by a broken line give the fuel consumption for

each period and show a wide variation from one period to the next. The points connected by an unbroken line give the average fuel consumption from the beginning of the test up to and including any period. In test 168 the results are very satisfactory. The average fuel consumption per brake horsepower per hour did not vary more than 1 per cent after the first 96 hours of the test; hence for this one test it is clear that 96 hours would have been sufficient for securing reasonably accurate results.

ESTIMATE OF PROPER TEST DURATION.

From the table it may be seen that the lack of uniformity in quantity of fuel consumed per period is due, in a great measure, to the corrections made for thickness of fuel bed. The graphic logs^a of these tests show that the thickness of the fuel bed throughout test No. 168 was comparatively uniform, although in tests 164, 165, and 166 the fuel-bed thickness varied considerably, and frequently there was a change of 8 to 10 inches during one period. These observations led to a study of the effect of change in thickness of the fuel bed and of the error in the calculations for fuel consumption due to inaccurate measurements. With the results of test No. 168 as a basis for comparison, an inspection of the other curves strengthens the impression that, with proper precautions regarding uniformity of fuel-bed depth, approximately 100 hours may be the required duration for tests on producers of this size and type, although this period may be influenced by the character of the fuel used.

SUMMARY AND TABLE.

From the above discussion it is evident: (a) That throughout a test the fuel bed should be maintained in uniform condition, with regard to both the character of the fire and the thickness of bed; (b) but that failing in this, special care should be exercised to see that the fuel bed is in the same condition and of the same thickness at the close of a complete test, or at the end of a test period, as at the beginning; (c) that a test should never be started when the producer has been standing idle for some time with "banked fires," as the fuel bed will not be in the average condition under which it will be required to work during the test; (d) that if, as the appointed hour for closing the test approaches, the fuel bed is not in the proper condition, the time of closing the test should be postponed until the bed naturally assumes the proper thickness and character. No forcing of conditions should be allowed simply to bring the test to an end at a previously determined hour.

^aThese logs for tests 25-168 will appear in a bulletin entitled "Producer-gas tests, 1905-1907," now in preparation for publication by the United States Geological Survey. The logs for tests 1-24, made in 1904, appeared in Prof. Paper U. S. Geol. Survey No. 48, part 3.

TABLE 1.—*Results of gas-producer tests at Norfolk.*

[Weights of coal in pounds.]

TEST No. 164.^a

No. of period.	Coal actually charged in producer.	Correction due to thickness of fuel bed.	Coal consumed.	Brake horsepower.	Coal per brake horse-power per hour.	Coal per brake horse-power per hour from beginning of test.
1.....	1,200	+ 292	1,492	225.6	0.83	0.83
2.....	1,200	- 292	908	240.8	.47	.65
3.....	1,500	+ 876	2,376	235.2	1.26	.85
4.....	1,500	+ 548	2,048	233.2	1.10	.92
5.....	1,650	0	1,650	235.0	.88	.91
6.....	1,800	+ 844	2,644	237.4	1.39	.99
7.....	2,250	-1,241	1,009	234.1	.54	.92
8.....	1,800	- 185	1,615	236.0	.86	.92
9.....	1,650	+ 591	2,241	237.1	1.18	.95
10.....	1,650	- 211	1,439	231.6	.78	.93
11.....	1,650	+ 454	2,104	236.9	1.11	.95
12.....	1,500	+ 621	2,121	239.1	1.11	.96
13.....	1,650	- 840	810	232.8	.44	.92
14.....	1,650	+ 183	1,833	240.4	.95	.92
15.....	1,500	+ 511	2,011	238.9	1.05	.93
16.....	1,800	+ 73	1,873	235.0	1.00	.93
17.....	1,500	- 91	1,409	240.7	.73	.92
18.....	1,350	+ 785	2,135	242.2	1.10	.93

TEST No. 165.^b

1.....	6,750	-2,646	4,104	238.1	0.72	0.72
2.....	4,950	+ 639	5,589	239.6	.97	.85
3.....	5,250	+ 165	5,414	241.0	.94	.88
4.....	4,800	+ 493	5,293	240.5	.92	.89
5.....	5,250	+ 292	5,542	240.1	.96	.90
6.....	4,800	- 402	4,398	236.0	.78	.88
7.....	6,150	- 621	5,529	240.1	.96	.89
8.....	5,400	- 876	4,524	238.4	.79	.88
9.....	4,800	-1,606	3,194	237.8	.56	.84
10.....	2,850	+3,001	7,851	239.8	1.36	.90

TEST No. 166.^b

1.....	4,350	+ 762	5,112	235.9	0.90	0.90
2.....	4,800	- 778	4,022	235.9	.71	.81
3.....	5,850	-1,342	4,508	231.7	.81	.81
4.....	4,800	+1,424	6,224	236.2	1.10	.88
5.....	4,800	- 563	4,237	235.5	.75	.85
6.....	5,100	+ 50	5,150	235.3	.91	.86
7.....	5,550	- 116	5,434	236.4	1.08	.89
8.....	4,950	+ 547	5,497	233.5	.98	.91
9.....	5,100	- 431	4,669	237.7	.82	.89

TEST No. 168.^b

1.....	4,500	+ 795	5,295	237.2	0.93	0.93
2.....	5,400	- 116	5,284	234.7	.94	.94
3.....	6,000	- 447	5,553	236.0	.98	.95
4.....	4,950	- 398	4,552	236.1	.80	.91
5.....	5,550	- 331	5,219	237.3	.92	.91
6.....	5,100	+ 215	5,315	235.2	.94	.92
7.....	5,250	+ 149	5,399	234.0	.96	.92
8.....	5,550	- 530	5,020	236.4	.88	.92
9.....	4,950	+ 149	5,099	237.0	.90	.92
10.....	5,400	+ 116	5,516	235.0	.98	.92

^a Divided into periods of 8 hours.^b Divided into periods of 24 hours.

TEMPERATURE DIFFERENCES IN FUEL BED.

By J. K. CLEMENT and H. A. GRINE.

PURPOSE AND METHOD OF EXPERIMENTS.

The object of the experiments here described was to determine as nearly as possible the differences of temperature in the fuel bed of the gas producer, and the influence of such differences on the chemical reactions taking place within the producer.

To allow the introduction of the pyrometer and gas-sampling tubes required in making these observations, a number of holes large enough to receive 1½-inch wrought-iron pipes were cut through the side of the producer, as shown in figure 3. The pipes projected about an inch beyond the outer shell of the producer and were provided with cast-iron caps.

Temperature measurements were made by means of a Le Chatelier platinum, platinum-rhodium thermocouple and a direct-reading semi-portable galvanometer. The thermocouple was calibrated from time to time by determinations of the melting points of zinc and copper, and the correction required by the deviation of the temperature of the cold junction from zero was applied.

The arrangement of the thermocouple is shown in figure 4. The wires were insulated by tubes of porcelain or fused silica, and the couple was inclosed in a large tube of one or the other of these materials. The outer tube was incased in a protecting tube of extra heavy wrought-iron pipe.

To determine the temperature in the hotter portion of the producer proved to be no easy undertaking. Frequently, owing to the compactness of the fuel bed, the iron tube had to be driven through the bed with a sledge hammer. Ten minutes, or longer, was required for the pyrometer to assume the temperature of the surrounding fuel.

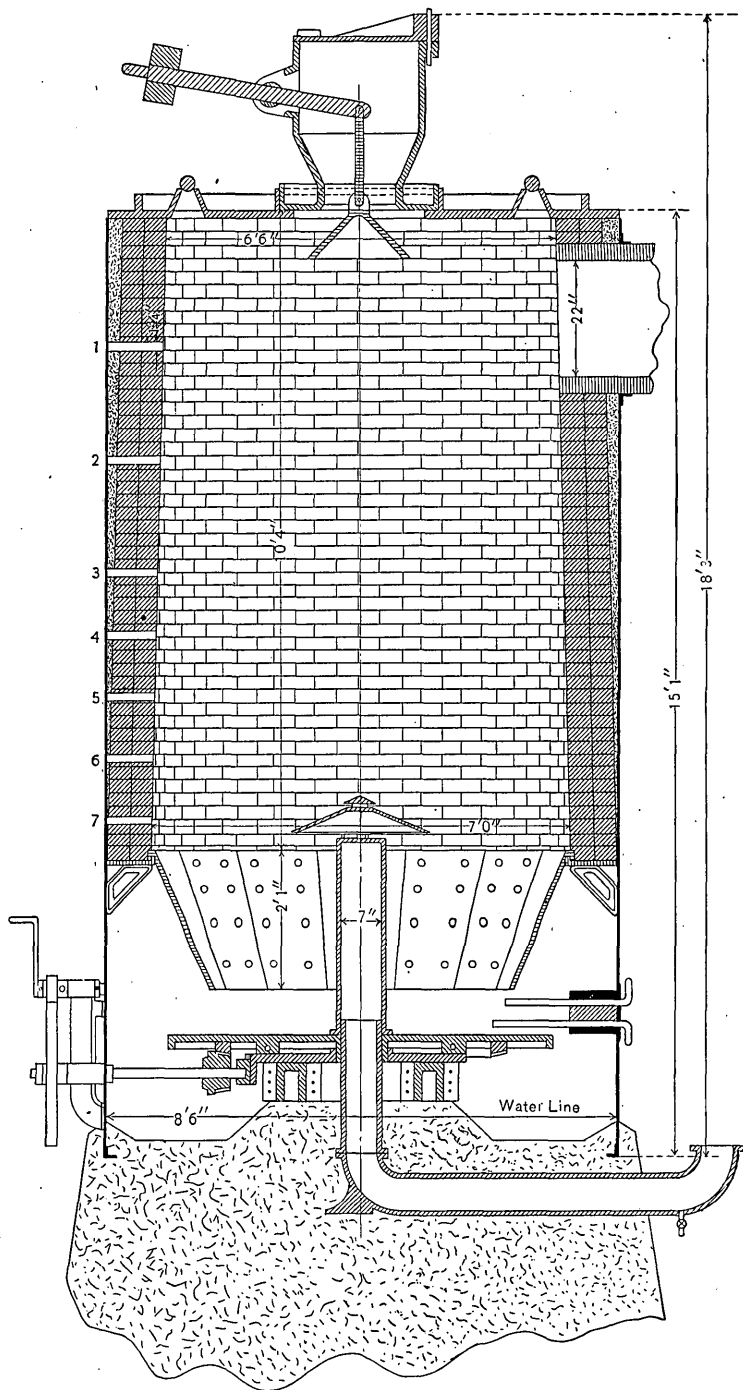


FIGURE 3.—Cross section of gas producer.

At the higher temperatures this time was sufficient for the iron pipe to bend and, with the aid of the reducing gases, to slag and break both the porcelain tube and the thermocouple.

When temperature observations were made, gas samples were usually taken. The sampling tube is shown in figure 5. In order to eliminate as far as possible any variation in the composition of the

gas through contact with a hot metallic surface, the tube was water jacketed to within $1\frac{1}{2}$ inches from the end.

The method of procedure was as follows: The pyrometer tube (fig. 4) was introduced through one of the holes in the side of the producer (see fig. 3), and observations made at different elevations and at any desired distance from the axis of the producer. To make a series of observations at one test hole required half an hour or more. The pyrometer tube was then withdrawn from the producer and the gas-sampling tube inserted in its place, and samples taken at several different places. When the desired number of observa-

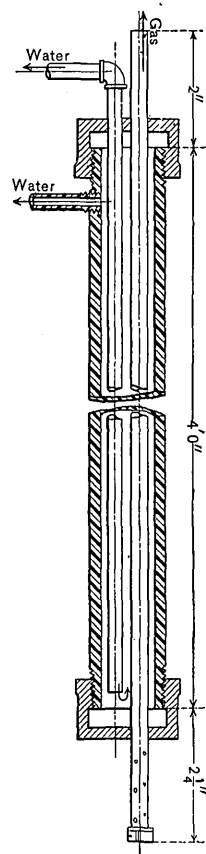


FIGURE 4.—Pyrometer tube.

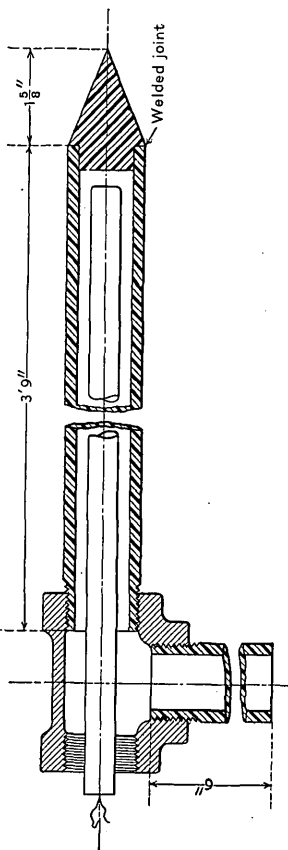


FIGURE 5.—Gas-sampling tube.

tions had been made at one test hole, the pyrometer tube was removed to another hole and the process repeated.

TEMPERATURE AT DIFFERENT HEIGHTS.

The first series of observations are contained in Tables 2 and 3. These results show that the temperature is highest, about $1,300^{\circ}\text{C}$., at a distance of 1 foot above the base of the hood. From this point upward the temperature falls gradually to 400°C . near the upper surface of the bed.

TABLE 2.—*Temperatures at specified points in gas producer.*

Date.	Number of test hole.	Height above base of hood.	Item No.	Distance from axis of producer.	Temperature.
		<i>Ft. in.</i>		<i>Inches.</i>	<i>°C.</i>
October 5.....	3	2 3	1	30	1,000
			2	10	1,142
			3	16	1,140
Do.....	2	1 3	4	16	1,140
			5	22	1,170
			6	28	1,060
			7	28	1,090
			8	34	1,015
October 7.....	1	0 3	9	7	1,075
			10	16	1,100
			11	28	425
Do.....	2	1 3	12	7	1,020
			13	16	1,140
			14	7	1,070
October 17.....	2	1 3	15	7	1,150
			16	16	1,265

TABLE 3.—*Temperature at specified points in gas producer, with analyses and British thermal units of gas samples taken at different heights.*

Date.	Height above base of hood.	Item No.	Distance from axis of producer.	Gas analysis.								British thermal units of gas per cubic foot.	Temperature.
				CO ₂ .	O ₂ .	C ₂ H ₄ .	CO.	H ₂ .	CH ₄ .	N ₂ .			
	<i>Ft. in.</i>		<i>Inches.</i>										<i>°C.</i>
October 26.....	5 3	1	22	6.5	0	0	24.7	14.0	1.8	53.0	154.1		550
		2	7										586
Do.....	4 3	3	16										510
		4	22	4.8	0	.4	25.6	17.4	2.4	49.4	182.1		
		5	28										823
Do.....	3 3	6	7										744
		7	16										708
		8	22	6.0	.2	.1	27.3	11.4	.6	54.4	138.8		
		9	28										1,009
Do.....	2 3	10	7										972
		11	16										1,148
		12	22	9.5	.1	.1	22.7	8.0	.9	58.7	123.8		1,150
		13	28										1,197
October 28.....	2 3	14	7										1,117
		15	16										1,176
		16	22	11.5	0	0	23.7	7.4	1.5	55.9	122.4		1,160
		17	28										1,205
Do.....	1 3	18	7	15.9	0	0	8.2	3.2	.3	72.4	43.1		1,230
		19	16										1,335
		20	22	9.0	0	0	22.7	8.2	.9	59.2	117.3		1,200
		21	28										1,072

A rapid fall of temperature from the lower part of the producer, where combustion is taking place, to the freshly fired fuel at the surface of the bed was to be expected, as was also the corresponding increase in the amount of combustible gases exhibited by the analyses in Table 3. In addition to this vertical temperature gradient, however, an unlooked-for horizontal temperature variation was observed.

DIFFERENT HORIZONTAL POSITIONS.

Table 3 shows that running through the center of the fuel bed, along the axis of the producer, is a region whose temperature is 300° or 400° C. below that of the outer portion of the bed. It seemed not

unlikely that the low temperature of the inner portion of the fuel bed would result in the formation of a gas lower in combustible constituents than the gas from the outer part of the bed. In order to determine, if possible, the extent of variation of the quality of the gas from the axis toward the wall of the producer, in connection with further temperature observations, gas samples were taken at varying distances from the axis of the producer. The results of observations made in this manner are contained in Table 4.

TABLE 4.—*Temperatures at specified points in gas producer, with analyses and British thermal units of gas samples taken at different heights and distances.*

Date.	Height above base of hood.	Item No.	Distance from axis of producer.	Gas analysis.							British thermal units of gas per cubic foot.	Temperature.
				CO ₂ .	O ₂ .	C ₂ H ₄ .	CO.	H ₂ .	CH ₄ .	N ₂ .		
	<i>ft. in.</i>		<i>Inches.</i>									<i>° C.</i>
November 6....	4 3	1	7	7.4	0	0	22.4	12.4	4.2	53.6	166.1	488
		2	16									488
		3	22									444
		4	28									597
		5	34	4.8	1.8	0	21.4	20.0	3.3	48.7	179.4	834
		6	7	10.5	0	0	23.2	16.8	1.2	48.3	152.2	639
		7	13									579
Do.....	3 3	8	16									565
		9	22									793
		10	28									913
		11	31									945
		12	34	5.2	0	0	30.7	12.8	.6	50.7	158.1	949
		13	7	4.0	0	0	18.8	24.6	6.0	46.6	215.1	311
		14	16									355
November 7....	3 3	15	22	4.6	0	0	21.4	26.6	4.8	42.6	218.4	794
		16	28									1,038
		17	34	5.6	0	0	26.1	13.6	.6	54.1	144.8	1,066
		18	7	5.0	0	0	27.4	17.8	1.5	48.3	173.5	512
		19	7	9.0	0	0	24.3	22.8	6.0	37.9	224.5	512
		20	7	5.9	0	0	29.3	12.6	.6	51.6	152.1	
		21	13									752
Do.....	2 3	22	16									969
		23	22									1,099
		24	28									1,174
		25	34	6.5	0	0	28.0	10.6	.6	54.3	141.0	1,169
		26	7	8.1	0	0	24.4	12.0	.6	54.9	132.9	1,190
		27	7	6.5	0	0	20.1	20.6	7.8	45.0	224.9	260
		28	16									260
November 8....	1 3	29	22									278
		30	28									698
		31	34	5.0	.3	0	21.4	24.4	4.2	44.7	204.3	845
		32	7									900
		33	16									390
		34	22									478
		35	28									611
Do.....	3 3	36	34	7.0	0	0	25.9	10.4	.6	56.1	133.0	1,096
		37										1,156

* Test 20 was made immediately after test 19. In test 19 the gas-sampling tube was water cooled and in test 20 it was uncooled.

In every case there is a rise of 300° or 400° C. from the interior to the exterior region of the fuel bed. Analyses of the gas samples fail to show any corresponding systematic variation in the amount of combustibles present. This can be explained, in part at least, by the circumstance that when the sampling tube was in position in the furnace, though an attempt was made to close the space between the sampling tube and the wall of the test hole, usually the excess pressure

within the producer forced a passage between sampling tube and producer wall, through which poured a current of hot gasses. Consequently a current of gas, drawn from all parts of the producer, is continually flowing past the end of the sampling tube, and the gas drawn through the sampler probably does not represent the normal condition at the point of sampling.

CAUSES OF IRREGULARITIES.

A comparison of the temperature observations of Table 4 shows that there is a considerable deviation between observations made at the same points in the fuel bed but on different days. The temperature at any point in the producer is dependent on the depth of fuel bed, the draft, poking, and firing. As these conditions can not be maintained absolutely constant, the temperature varies accordingly. In order to obtain results which are strictly comparable, temperature measurements and gas sampling should take place simultaneously in various parts of the fuel bed. This is obviously impossible on account of the great amount of apparatus that would have to be handled and the rapidity with which the pyrometer and sampling tubes are attacked and destroyed in the hotter parts of the fuel bed. So much time was required for each observation that relatively few could be made in one day. Moreover, during a series of observations extending over a day, the condition of the fuel bed was continually changing, so that results obtained on the same day may disagree.

AVERAGE RESULTS FOR EACH POINT.

In Table 5 all the results in Tables 2, 3, and 4 have been combined by averaging the observations for each point in the producer. The observations are grouped with respect to their distance from the axis and in the order of their height above the hood.

TABLE 5.—Average of observed temperatures and gas analyses for specified points in gas producer, grouped by distances from axis.

Distance from axis of producer.	Height above base of hood.	Gas analysis.					British thermal units of gas per cubic foot.	Tem- pera- ture.
		CO ₂ .	CO.	H ₂ .	CH ₄ .	N ₂ .		
	<i>Ft. in.</i>							°C.
7 inches.....	4 3	7.0	21.2	16.5	6.0	49.3	195.5	445
	3 3	7.2	21.0	20.7	3.6	47.4	183.6	521
	2 3	6.4	27.5	16.4	2.1	47.3	175.5	867
	1 3	12.0	16.3	7.6	.45	63.6	88.0	1,151
	4 3							419
16 inches.....	3 3							526
	2 3							1,098
	1 3							1,220

TABLE 5.—Average of observed temperatures and gas analyses for specified points in gas producer, grouped by distance from axis—Continued.

Distance from axis of producer.	Height above base of hood.	Gas analysis.					British thermal units of gas per cubic foot.	Temperature.
		CO ₂ .	CO.	H ₂ .	CH ₄ .	N ₂ .		
	<i>Ft. in.</i>							°C.
22 inches.....	4 3	4.8	25.6	17.4	2.4	49.4	182.1	515
	3 3	5.3	24.3	19.0	2.7	48.5	178.6	877
	2 3	10.5	23.2	7.7	1.2	57.3	123.1	1,140
	1 3	9.0	22.7	8.2	.9	59.2	117.3	1,185
	4 3							706
28 inches.....	3 3							1,014
	2 3							1,144
	1 3							1,074
	4 3	4.9	21.4	22.2	3.7	46.7	191.8	840
34 inches.....	3 3	5.9	27.6	12.3	.6	53.6	145.3	1,057
	2 3	6.5	28.0	10.6	.6	54.3	141.0	1,169
	1 3							1,015

The variations both of temperature and of composition of gases are more marked than in the preceding tables. The temperature

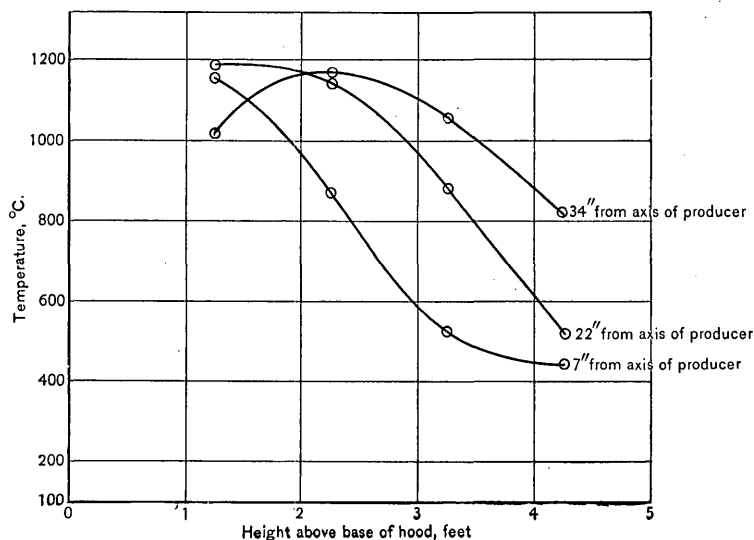


FIGURE 6.—Curves of temperature variation with height above base of fuel bed.

gradients along vertical lines located 7, 22, and 34 inches from the axis are illustrated graphically in figure 6. Here the curve for the temperatures nearest the axis (7 inches) falls rapidly from 1,150° to 500° C. The middle curve of temperatures, midway between axis and wall, is flat for a distance representing a foot or more in height and then falls off as it approaches the top of the fuel bed. Finally the top curve for temperatures, near the furnace wall, rises gradually to a maximum and then falls off slowly. The low temperature at the

lower part of the fuel bed and near the wall is due to the accumulation of ashes at that point.

These temperature variations are further illustrated in figure 8, in which curves are drawn through points of equal temperature. The absolute temperature at any point in the fuel bed varies with the conditions of operation—for example, with the depth, draft, poking, and grinding of the bed. The curves in figure 8 have therefore a relative value only. They serve to show, however, that running through the center of the fuel bed is a region of low temperature, 300° to 400° C. below the temperature of the outer zones.

PROCESS OF GAS FORMATION.

In addition to combustion, the two principal reactions that take place in the producer are $\text{CO}_2 + \text{C} = 2\text{CO}$ and $\text{H}_2\text{O} + \text{C} = \text{CO} + \text{H}_2$. The temperature in the central portion of the fuel bed is so low that these reactions can not take place there to an appreciable extent. Consequently a considerable proportion of the producer fuel bed is not effective in forming producer gas, and the producer is operating at a far lower capacity than if the temperature of the inner region were maintained equal to that of the outer zone.

Figure 8 furnishes an explanation of the irregular temperature distribution in the fuel bed. The current of air and steam proceeding from the mouth of the blower at *a* has two paths open to it, one straight ahead through *c* and one under the base of the hood at *b*. From the direction of the isothermal lines in figure 8, it seems likely that the greater portion of the incoming air passes out under the base of the hood and up through the outer part of the fuel bed. Either the opening at *c* is too small or it is clogged with ash and fuel.

In Table 5 the process of formation of producer gas may be traced roughly in each of the three groups of samples. The proportion of CO_2 and nitrogen decreases in each group from the level of test hole No. 2, which is a foot above the hood, to the surface of the fuel bed. There is a marked increase in the percentage of hydrogen and methane (CH_4) from the lower to the upper test hole. A corresponding increase in the amount of carbon monoxide (CO) might be expected. The CO values in Table 5, however, exhibit no systematic variation.

The variations are more clearly shown in Table 6, in which the means of all the values for each height, irrespective of distance from the axis, are arranged in the order of the height of the points of observation above the hood.

TABLE 6.—Average of observed temperatures and gas analyses for specified heights, irrespective of distance, in gas producer.

Height above base of hood.	Gas analysis.					British thermal units of gas per cubic foot.	Temperature.
	CO ₂ .	CO.	H ₂ .	CH ₄ .	N ₂ .		
Gas leaving producer.....	7.2	22.9	15.0	1.8	53.1	152.9	°C.
4 feet 3 inches.....	5.6	22.7	18.7	4.0	48.5	189.8	585
3 feet 3 inches.....	6.1	24.3	17.3	2.3	49.8	169.2	799
2 feet 3 inches.....	7.8	26.2	11.6	1.3	53.0	146.5	1,084
1 foot 3 inches.....	10.5	19.5	7.9	.7	61.4	102.6	1,129

The values of Table 6 are represented graphically by the curves in figure 7. The vertical line at the right of the figure (abscissa=5 feet

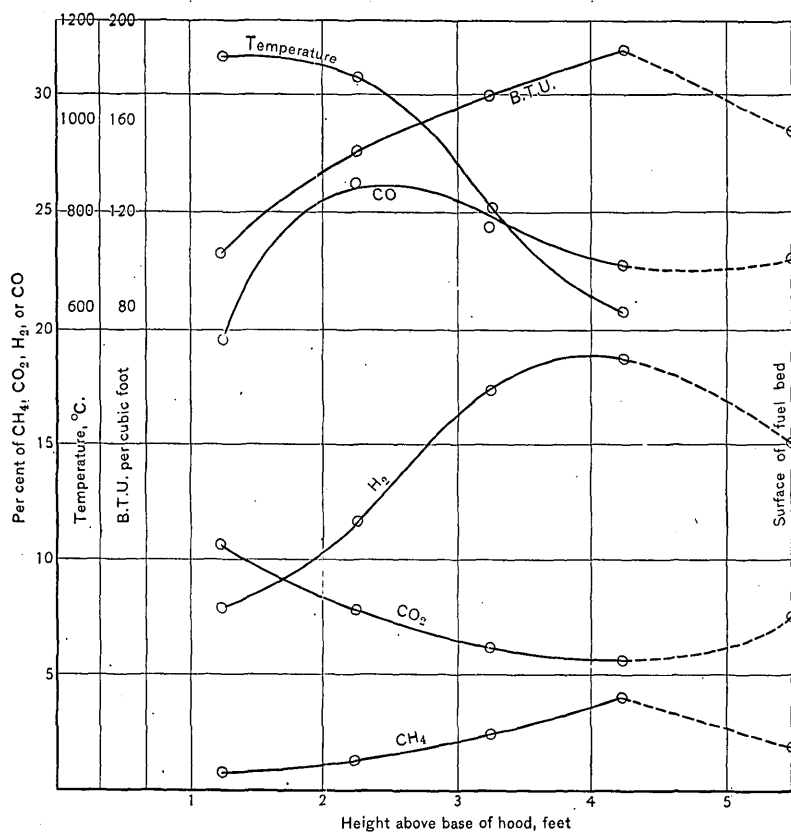


FIGURE 7.—Variation of gas combustion temperature and British thermal units with height above base of fuel bed.

6 inches) represents the approximate level of the surface of the fuel bed. The points lying on this line and connected with the appropriate curves by means of dotted lines are the mean values of the percentage of the various gases and of the calorific values in British thermal

units for the gas leaving the producer. The data are taken from the official gas analyses. The temperature is that of the gas just above the fuel bed.

The conclusions or results shown by Table 6 and figure 7 are of interest only as a confirmation of the generally accepted theory of the gas producer and offer nothing novel.

DIFFERENCES WITH DISTANCE FROM AXIS.

In Table 7 the results of Table 5 have been grouped in accordance with their height above the base of the hood, to permit a comparison of gas samples taken from the same height in the producer but at different distances from the axis.

TABLE 7.—Average of observed temperatures and gas analyses for specified points in gas producer, grouped by heights.

Height above base of hood.	Distance from axis of producer.	Gas analysis.					British thermal units of gas per cubic foot.	Temperature.
		CO ₂ .	CO.	H ₂ .	CH ₄ .	N ₂ .		
	<i>Inches.</i>							°C.
4 feet 3 inches	7	7.0	21.2	16.5	6.0	49.3	195.5	445
	16							419
	22	4.8	25.6	17.4	2.4	49.4	182.1	515
	28							706
	34	4.9	21.4	22.2	3.7	46.7	191.8	840
3 feet 3 inches	7	7.2	21.0	20.7	3.6	47.4	183.6	521
	16							526
	22	5.3	24.3	19.0	2.7	48.5	178.6	877
	28							1,014
	34	5.9	27.6	12.3	.6	53.6	145.3	1,057
2 feet 3 inches	7	6.4	27.5	16.4	2.1	47.3	175.5	867
	16							1,098
	22	10.5	23.2	7.7	1.2	57.3	123.1	1,140
	28							1,144
	34	6.5	28.0	10.6	.6	54.3	141.0	1,169
1 foot 3 inches	7	12.0	16.3	7.6	.45	63.6	88.0	1,151
	16							1,220
	22	9.0	22.7	8.2	.9	59.2	117.3	1,185
	28							1,074
	34							1,015

It has been shown above (p. 22 and fig. 8) that the low temperature of the interior of the producer is not favorable to the formation of CO and H₂. It was to be expected, therefore, that samples taken in the outer portions of the fuel bed would show a higher percentage of H₂ and CO and a lower percentage of CO₂ than those taken along the same radius nearer the axis of the producer.

Assuming that the temperature distribution in the producer is represented correctly by the curves of figure 8, and assuming further that the lines of flow of the gas are approximately vertical, then samples from the same level, up to the level of test hole No. 3, should not be expected to show any great variation.

Above the level of hole 3 the temperature of the interior of the bed is below the temperature necessary for the formation of appreci-

able quantities of CO and H_2 . A marked difference might therefore be expected between samples from the inner and outer portions of the bed taken through test hole 4 or 5. Table 7 does not show any such systematic difference. Whereas at an elevation of 4 feet 3 inches above the base of the hood (hole 5) the hydrogen content is appreciably higher near the wall of the producer than near the axis, the

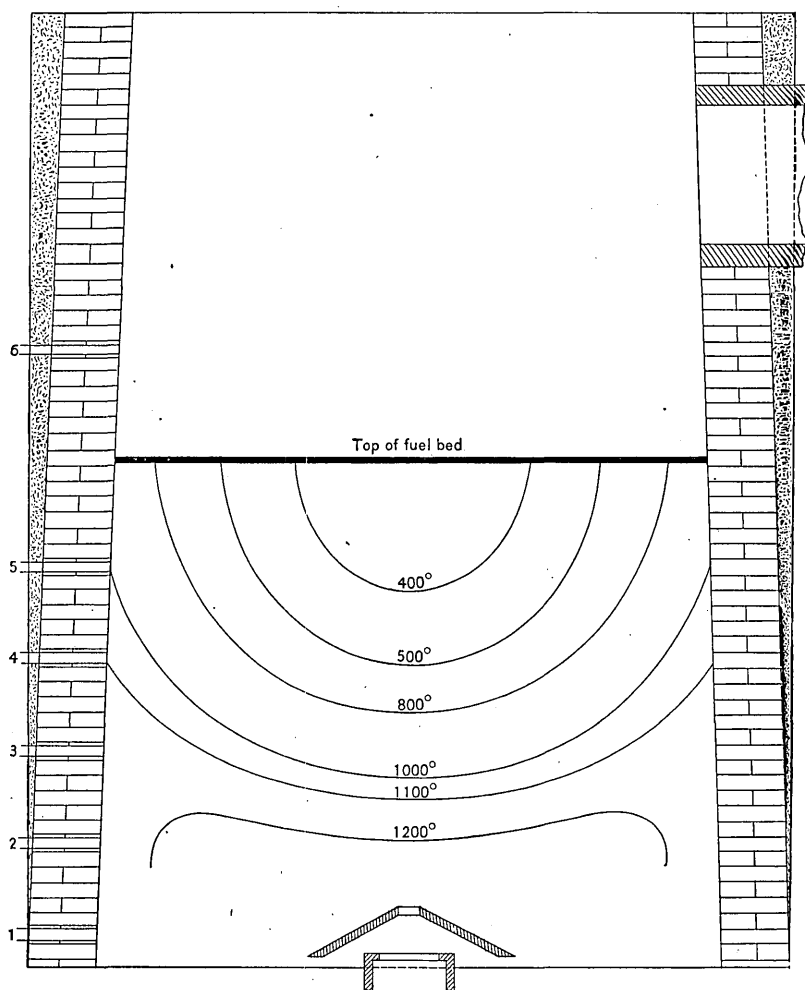


FIGURE 8.—Section of producer showing temperature variation for height and distance from sides of producer.

samples taken a foot lower (hole 4) show a variation in the opposite direction. The methane content alone shows a systematic variation, being higher in samples from the inner portion of the bed. This is probably because methane, being readily liberated at relatively low temperatures, is mostly given off before the coal reaches the hot region of the outer zone.

REQUISITE TEMPERATURE FOR FORMATION OF CO.

The experiments show a gradual increase in the amount of combustible constituents and a corresponding decrease in the amount of CO_2 from the level of test hole 2 to the surface of the bed. While the percentage of hydrogen is more than doubled between holes 2 and 5, the increase in CO is less than a fourth as great. Apparently the formation of CO from CO_2 takes place for the most part below hole 2, in the lower part of the bed.

The analyses of gas samples offer no evidence to confirm the supposition that the lower temperature of the inner portion of the bed would give rise to a gas lower in CO and H_2 than that of the outer regions. These facts especially made it desirable to determine, if possible, the temperature requisite for the formation of gas rich in CO and H_2 , or in other words to determine at what temperatures the reaction $\text{CO}_2 + \text{C} = 2\text{CO}$ and $\text{H}_2\text{O} + \text{C} = \text{CO} + \text{H}_2$ may be complete.

An extensive series of investigations on the relative proportions of CO_2 and CO in equilibrium with carbon at different temperatures has been carried out by Boudouard.^a He found the respective percentages of CO_2 and CO in equilibrium with carbon at 650°C. to be 61 and 39; at 800°C. , 7 and 93; and at 925°C. , 4 and 96.

These results of Boudouard have been used by writers on the theory of the gas producer to demonstrate the temperature in the fuel bed necessary for the formation of rich CO gas. Boudouard's results apply to mixtures of CO_2 and CO which have been in contact with hot carbon for a considerable length of time—until equilibrium has been reached. In his experiments at 650° and 800°C. sealed glass tubes containing carbon and CO_2 were heated for a period of several hours.

Since for the reaction $\text{CO}_2 + \text{C} = 2\text{CO}$ an appreciable amount of time is required—that is, the reaction does not take place instantaneously—the direct application of Boudouard's results to the process in the gas producer, in which the gas rushes through the fuel bed at a high velocity is not justifiable. Recent experiments under the direction of one of the authors of this report, the results of which will be published in forthcoming bulletins, have established that, with the rate of flow of gas and the depth of fuel bed which obtain in a gas producer a temperature of $1,100^\circ \text{C.}$ or more is required for the formation of 90 per cent CO gas from CO_2 and charcoal, and $1,300^\circ$ for the same percentage from CO_2 and coke and from CO_2 and anthracite coal. With a temperature 100°C. lower than these the resultant gas will contain about 50 per cent CO. It follows that the temperature of the fuel bed of the gas producer must be at least $1,300^\circ \text{C.}$ in order to yield the highest possible percentage of CO.

^a Boudouard, *Compt. Rend. Acad. Sci. Paris*, vol 28, 1899, pp. 824, 1542; vol. 130, 1900, p. 132; vol. 131, 1900, p. 1204. See also Haber, *Thermodynamics of technical gas reactions*, London, 1908, p. 311.

SUMMARY.

1. Temperature observations were made and gas samples taken in different parts of the fuel bed of the gas producers. The temperature was found to be highest at the bottom of the fuel bed and to decrease from this point to the top of the bed.

2. The temperature of the inner region of the fuel bed was found to be 300° or 400° lower than that of the outer layers. A corresponding inferiority in the quality of the gas in the center of the producer could not be established; probably on account of the defective method of sampling.

3. It has been suggested that by an improvement in the method of admitting the draft to the fuel bed a more uniform distribution of temperature, and consequently a gain in the capacity of the producer and in the quality of the gas, might be obtained.

4. Reference has been made to recent experiments by one of the authors which have established $1,300^{\circ}$ C. as the lower limit of temperature for the formation of a gas rich in CO.

SURVEY PUBLICATIONS ON FUEL TESTING.

A classified list of Survey papers dealing with coal is given in Bulletin 316, and in an abstract from that bulletin, pp. 439 to 532, published separately.

The following publications on fuel testing, except those to which a price is affixed, can be obtained free by applying to the Director, Geological Survey, Washington, D. C. The priced publications can be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C.

BULLETIN 261. Preliminary report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, in St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1905. 172 pp. 10 cents.

PROFESSIONAL PAPER 48. Report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1906. In three parts. 1492 pp., 13 pls. \$1.50.

BULLETIN 290. Preliminary report on the operations of the fuel-testing plant of the United States Geological Survey at St. Louis, Mo., 1905, by J. A. Holmes. 1906. 240 pp. 20 cents.

BULLETIN 323. Experimental work conducted in the chemical laboratory of the United States fuel-testing plant at St. Louis, Mo., January 1, 1905, to July 31, 1906, by N. W. Lord. 1907. 49 pp. 10 cents.

BULLETIN 325. A study of four hundred steaming tests, made at the fuel-testing plant, St. Louis, Mo., 1904, 1905, and 1906, by L. P. Breckenridge. 1907. 196 pp. 20 cents.

BULLETIN 332. Report of the United States fuel-testing plant at St. Louis, Mo., January 1, 1906, to June 30, 1907; J. A. Holmes, in charge. 1908. 299 pp.

BULLETIN 334. The burning of coal without smoke in boiler plants; a preliminary report, by D. T. Randall. 1908. 26 pp. 5 cents.

BULLETIN 336. Washing and coking tests of coal and cupola tests of coke, by Richard Moldenke, A. W. Belden, and G. R. Delamater. 1908. 76 pp. 10 cents.

BULLETIN 339. The purchase of coal under government and commercial specifications on the basis of its heating value, with analyses of coal delivered under government contracts, by D. T. Randall. 1908. 27 pp. 5 cents.

BULLETIN 343. Binders for coal briquets, by J. E. Mills. 1908. 56 pp.

BULLETIN 362. Mine sampling and chemical analyses of coals tested at the United States fuel-testing plant, Norfolk, Va., in 1907, by J. S. Burrows. 1908. 23 pp. 5 cents.

BULLETIN 363. Comparative tests of run-of-mine and briquetted coal on locomotives, by W. F. M. Goss. 1908. 57 pp.

BULLETIN 366. Tests of coal and briquets as fuel for house-heating boilers, by D. T. Randall. 1908. 44 pp.

BULLETIN 367. Significance of drafts in steam-boiler practice, by W. T. Ray and Henry Kreisinger. 1909. 61 pp.

BULLETIN 368. Washing and coking tests of coal at Denver, Colo., by A. W. Belden, G. R. Delamater, and J. W. Groves. 1909. 54 pp., 2 pls.

BULLETIN 373. The smokeless combustion of coal in boiler plants, by D. T. Randall and H. W. Weeks. 1909. 188 pp.

BULLETIN 378. Results of purchasing coal under government specifications, by J. S. Burrows; Burning the small sizes of anthracite for heat and power purposes, by D. T. Randall. 1909. 44 pp.

BULLETIN 385. Briquetting tests at Norfolk, Va., by C. L. Wright. 1909. 41 pp., 9 pls.

BULLETIN 392. Gasoline and alcohol tests on internal-combustion engines, by R. M. Strong. 1909.

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